COMBATING THE TYRANNY OF SCALE FOR HALIOTIDS: MICRO-MANAGEMENT FOR MICROSTOCKS

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ABSTRACT

Global production of Haliotids (abalone) declined more than 60% since the 1960s and continues to decline, indicating a failure to manage these resources sustainably. This paper discusses facets of abalone biology which make sustainable management problematic. Abalone resources are comprised of many small (100s–1000s m) self-recruiting microstocks with highly variable sizes-at-maturity. This causes a mis-match between the scale of management and the scale of component units of stock. This "tyranny of scale" leaves component microstocks vulnerable to the "tragedy of the commons" and resources vulnerable to serial depletion despite apparently rigorous regional scale management. I postulate that beyond abalone, and across a range of spatial scales, unrecognized spatial complexity compromises monitoring, assessment, and management in many fisheries. I suggest that a major challenge for abalone fisheries and the field of fisheries more generally, is to adapt the scale of fisheries monitoring, assessment, and management to the actual scale of component units of stocks, and to mobilize the resources required to adequately address the global needs of a myriad of microstocks. An increased use of territorially based fishing rights and a new class of fisheries practitioners are proposed as part of the answer to this challenge.

Haliotids, or abalone as they are commonly known, are herbivorous mollusks that graze and catch drift algae in shallow (0–35 m) reef environments around the major continents of the world. Abalone are characterized by their ear-like shape and the row of respiratory pores running round the whorl of the shell. Their fleshy feet and bowl-like shells have been exploited in many countries since Paleolithic times (Cox, 1962). Today, about one quarter of the 75 living species are fished commercially (Mottet, 1978). They are pried or hooked off rocks by divers or waders, and mainly sold as a luxury item in Chinese and Japanese markets around the world (Tegner, 1989).

Global Trends

The figures produced by FAO on global Haliotid production suggest that global production peaked in 1968 at 27,600 t yr^{-1} (Fig. 1). Soon afterwards production from the major stocks of California and Mexico declined sharply (Tegner, 1989; Guzmán del Próo, 1992). During the late 1970s, Australia began controlling production levels, and during the 1980s reduced production from around 8000–5000 t with systems of individual transferable quotas (ITQ) (Prince and Shepherd, 1992). Despite massive Japanese investment in stock enhancement, reseeding, and ocean ranching, production has slowly declined from 6500 t in 1970 to around 2300 t in 1998 (Saito, 1979, 1984; Mottet, 1980; Kojima, 1995). By the late 1980s, global annual production had declined to around 15,000 t yr^{-1}, and by the start of the new millennium, global abalone production was ~10,000 t yr^{-1} and still declining.

The decline in global abalone production is indicative of a global failure to sustain production from wild stocks of abalone, and the continuing failure to significantly
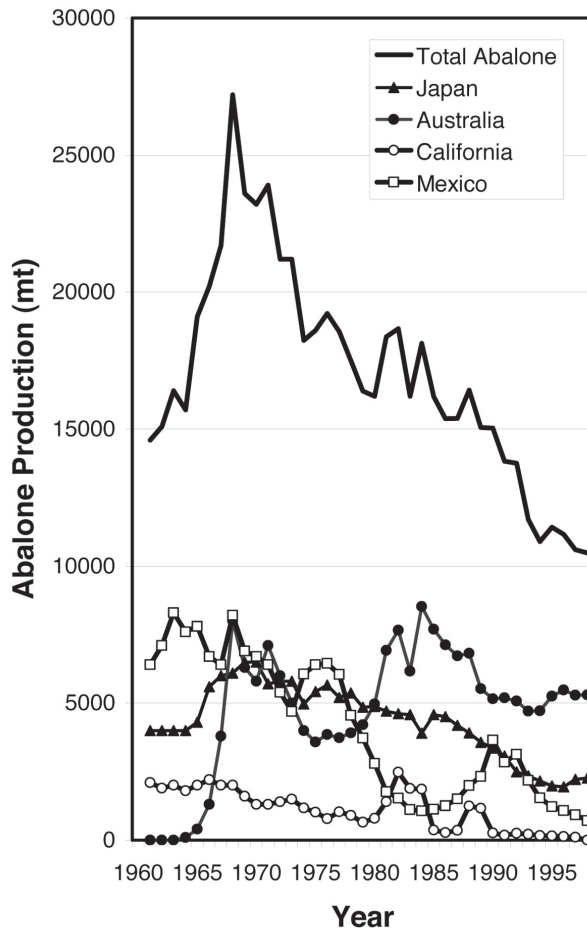
Figure 1. Global figures for abalone production collated by FAO for 1960–2000 showing trends for total production and production by the world's four major producers; Japan, California, Mexico, and Australia. These data inadequately reflect production by mariculture, and for local consumption, but are still indicative of global production trends.

augment production through mariculture or ocean ranching. In this paper I discuss the aspects of abalone biology and fisheries ecology that have conspired against sustaining abalone production, and propose changes that are needed to reverse current production trends.

The Fisheries Ecology of Abalone

In response to concern about stock status during the 1980s, the Australian Commonwealth Fishing Industry Research Trust Account (now the Fisheries Research and Development Corporation) began to support parallel abalone research programs in the states of South Australia, New South Wales, Victoria, and Tasmania. Together, these programs described a combination of factors that conspired against sustainable abalone production.

Understanding resulted primarily from the application of shell aging techniques developed originally in Japan (Prince et al., 1988a), and the development of techniques for finding juvenile abalone (Prince and Ford, 1985; Shepherd and Turner, 1985; McShane and Smith, 1988a). These may appear to be basic steps, but until that time researchers had failed to sample juveniles adequately and it had become an accepted part of scientific dogma that broadcast spawning by abalone was inefficient and resulted in relatively few settled juveniles. Recruitment to abalone populations has often been assumed to normally be low and sporadic (Hayashi, 1980; Sainsbury, 1982a,b; Tegner, 1989). Consequently, abalone populations have been expected to contain few juveniles, with high "adult-like" survival rates (~0.2 yr^{-1}) leading to the accumulation of long lived adults in abalone stocks (Hayashi, 1980; Sainsbury, 1982a,b; Shepherd et al., 1982; Tegner, 1989).

When reading the literature, however, it must be remembered that even today few researchers have studied natural populations of juvenile abalone (Prince and Ford, 1985; Shepherd and Turner, 1985; McShane and Smith, 1988a; Prince, 1989; McShane, 1992; Day and Shepherd, 1995). Juvenile abalone live cryptically wedged into reef crevices (which are almost impossible to sample quantitatively) and emerge onto the surface of the reef as they mature (Prince et al., 1988b). The extent to which juveniles can be discovered by destruction of the boulder habitat, or any other technique, is entirely dependent on the geology of the substrate. As discussed below, the inability to find juveniles has had a pernicious impact on the quality of published knowledge of abalone, much of which still requires correction.

High Juvenile Mortality Rates

Once juvenile populations were sampled in ways that began to capture their real abundance (Fig. 2), it became evident that juveniles were extremely abundant relative to adults, and suffered much higher rates of natural mortality (Prince et al., 1988b). McShane and Smith (1988a) observed settlement at densities exceeding 10^3 animals m^{-2} while Prince et al. (1988b) estimated annual rates of natural mortality during the first few years of at least 0.8–1.5. As reviewed by Shepherd and Breen (1992), a mounting body of evidence shows that populations of young abalone are dynamic and have high rates of turnover. Interestingly, this confirms earlier conclusions of Hines and Pearse (1982), who observed small populations of young abalone persisting in Monterrey Bay under heavy sea otter predation.

Growth Studies

The failure of scientific technique extends into the study of abalone growth. Because of the difficulty of sampling juvenile populations, and an apparent reluctance to grind shells, most growth studies of wild abalone populations have concentrated on tagging the emergent sub-adult and adult populations. The data gathered for the adults is then fitted to von Bertalanffy curves using standard software packages and, without information to the contrary, the standard practice has been to assume that t_0 of the von Bertalanffy equation is zero. The median age of each inferred age classes has then been extrapolated solely on the basis of adult growth rates.

Studies on juvenile modal progression and direct ageing of shells (Prince et al., 1988a; Prince, 1989; Nash, 1992) clearly show that abalone growth through life cannot be described with the von Bertalanffy model. Moreover, t_0 for the von Bertalanffy equation should be 2–4 yrs. Juvenile growth through to maturity is generally 2–4 yrs
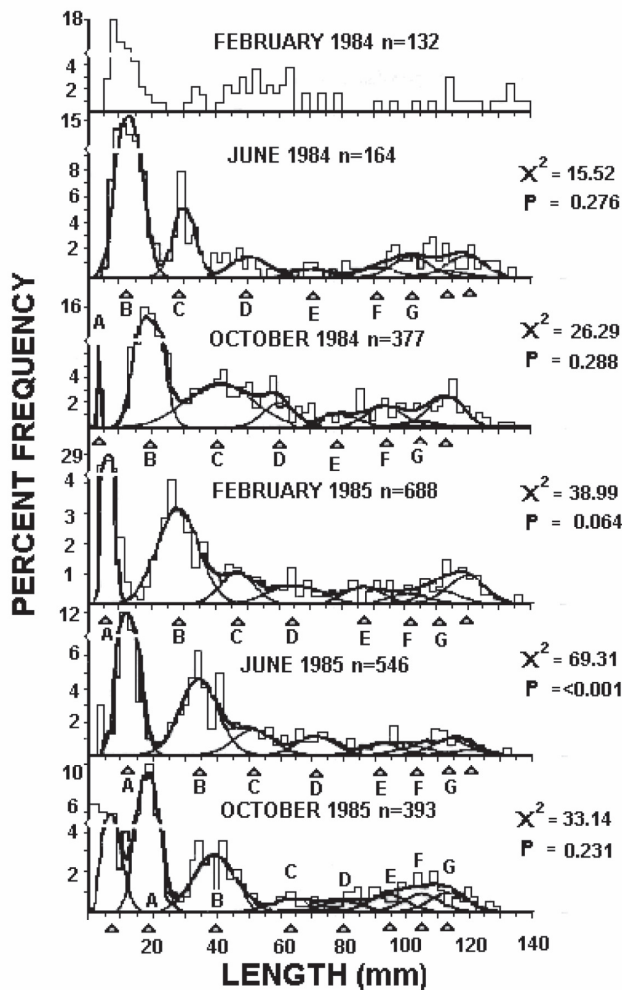
Figure 2. Length frequency histograms for *Haliotis rubra*, sampled at Blubber Head, southern Tasmania in Australia between February 1984 and October 1985. Histograms show that abalone juveniles are abundant and have high rates of natural mortality compared to adults. This figure is reproduced from Prince et al. (1988b).

slower than suggested by a von Bertalanffy curve extrapolated back to $t_0 = 0$. Abalone growth is better described with a sigmoid curve, such as the Gompertz model, or even with a piecewise fit, with linear juvenile growth up to a von Bertalanffy curve describing adult growth (Fig. 3).

The implication of this is that without good samples of juveniles to allow juvenile growth to be described accurately many abalone growth studies have underestimated the age-at-maturity by 2–4 yrs (e.g., Shepherd and Hearn, 1983; Keesing and Wells, 1989; Tegner et al., 1992; Tarr, 1995; Wells and Mulvay, 1995). These mistakes in the literature are still inflating expectations of productivity for would-be mariculturists, sea-ranchers, and managers, whilst leading other researchers to doubt the effectiveness of ageing shells because tagged "ages" cannot be made to agree with a pattern of ring counts (e.g., McShane and Smith, 1988b).
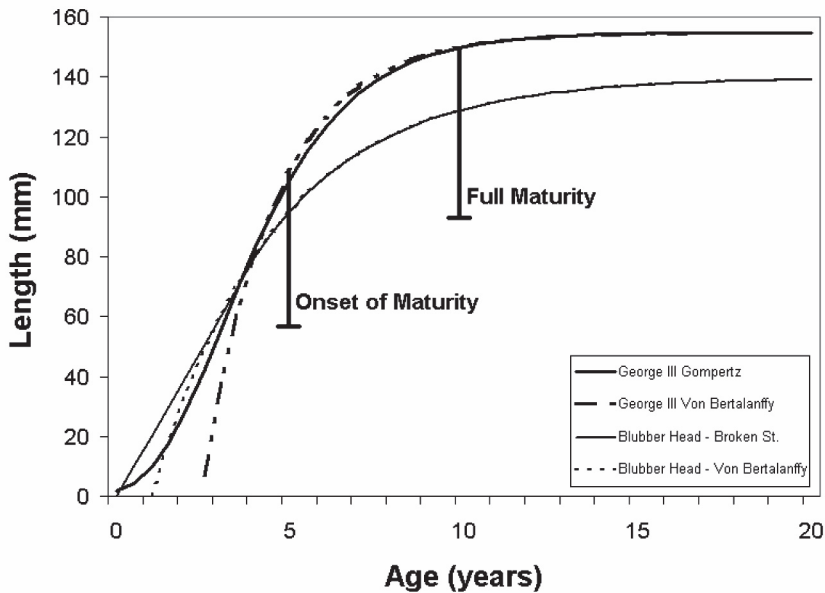
Figure 3. Comparative growth curves of *Haliotis rubra*, at Blubber Head (thin lines) and George III Rock (thick lines) southeastern Tasmania estimated by Prince (1989). For each site Von Bertalanffy curves (dotted lines) estimated from tag return studies of emergent abalone were compared with alternative curves derived from more complete data (solid lines). The alternative George III Rock growth curve is a Gompertz curve fitted by ageing shells. The alternative Blubber head curve is a "broken-stick" curve comprised of a straight line fitted to length-at-age data derived from length-frequency histograms (Fig. 2) for <80 mm size classes and von Bertalanffy parameters derived from tag-return data >80 mm. The size and age at the onset and completion of maturation as derived by Prince (1989) is also indicated for each site (see Fig. 4).

RESTRICTED MOVEMENT AND DISPERSAL

Once juveniles could be found soon after settlement, it was possible to test the theory that abalone larval dispersal occurred over distances of 70–90 km (Tegner and Butler, 1985). Manipulating adult densities in wild stocks and examining the resulting density patterns of recently settled juveniles (Prince et al., 1987, 1988c) led to the conclusion that, like adult movements, larval dispersal is generally limited to scales of tens to hundreds of meters (McShane et al., 1988; Brown, 1991; Shepherd and Brown, 1993).

Important implications for the management of wild stocks of abalone flow from this observation. Specifically, abalone fisheries are not sustained by the single, freely mixing "units" of stock (Gulland, 1969) assumed by most management and assessment models. Instead they are comprised of many (thousands to tens of thousands) relatively independent aggregations each of which is a relatively self-recruiting unit, or microstock. Population exchange occurs between component populations within the broader meta-population (Shepherd and Brown, 1993) but these exchanges occur at relatively low rates. Genetic distance is entirely proportional to the distance of separation even at the smallest scales (Brown, 1991).

In itself this need not be a problem. If microstocks were biologically similar and fishing pressure was distributed evenly so that fishing mortality was similar for each microstock, their number and scale would have little implication for assessment and management (Fukuda, 1973; Garrod, 1973). If this were the case, component mi-
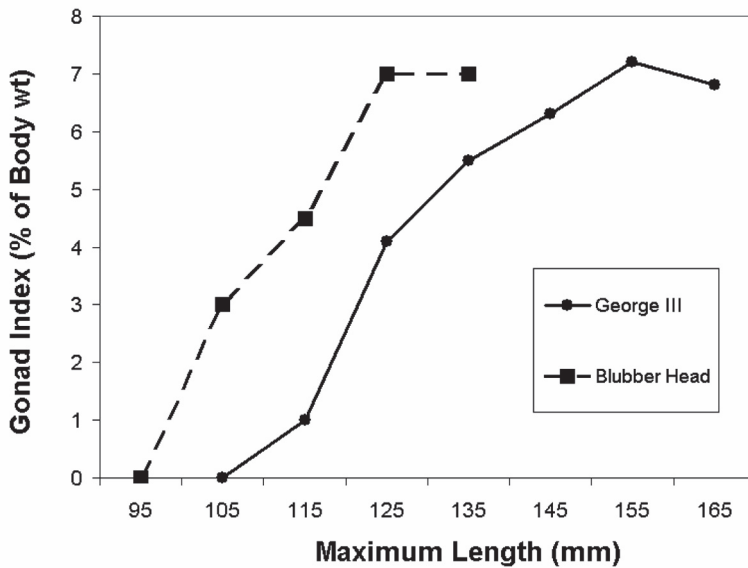
Figure 4. The relationship between maturity and length for *Haliotis rubra*, sampled at George III Rock (solid line) and Blubber Head (dotted line), southern Tasmania, as derived by Prince (1989). In combination with Figure 3, these ogives illustrate that maturation in abalone tends to be age-determined while the size-at-maturity is variable.

crostocks could be managed in aggregate, and regional management should work irrespective of the small-scale metapopulation structure.

VARIABLE PATTERNS OF GROWTH AND FECUNDITY

Growth is naturally extremely plastic, however, adapting to an extreme range of local conditions (Leighton and Boolootian, 1963; Sloan and Breen, 1988; Day and Fleming, 1992). It is highly variable among individuals and populations living short distances apart (1–1000 m) and across the geographic range of each species. Interestingly, and contrary to general expectation, maturity is principally determined by age, rather than size (Shepherd and Laws, 1974; Prince, 1989; McShane, 1991; Nash, 1992). Thus, populations of the same species commence breeding at the same age over broad regions, while the size-at-maturity and maximum size attained varies widely over all geographic scales.

Figures 3 and 4 illustrate this point for blacklip abalone (*Haliotis rubra* Leach, 1816) populations ~15 km apart in southeastern Tasmania (Prince, 1989). Notice the same general shape of the growth curves (Fig. 3) from two nearby locations; relatively linear or even sigmoidal juvenile growth, slowing gradually with the onset of maturity around 5 yrs old (Fig. 4) and slowing rapidly by 10 yrs old when almost the entire population is mature (Figs. 3,4). Notice, in particular, the 20 mm size difference in average maximum size between these two haphazardly selected sites, the implication of this is that a 132 mm commercial size limit allows the fishery to harvest 7 yr old abalone on George III Rock while protecting 11 yr old abalone at Blubber Head (Fig. 3).

My observations suggest size at the onset of maturity for blacklip abalone through its range down the southeastern coast of Australia varies from around 60–200+ mm;

size-at-maturity of the paua of New Zealand (*Haliotis iris* Martyn) varies to a similar degree (Naylor and Andrew, 2001). This variation is observed as a cline from north to south in both countries, but also between adjacent sheltered and exposed shorelines. In contrast to the size-at-maturity, the age of full maturity for each species tends to be conservative over broad regions.

Commercial divers in every abalone fishery refer to abalone found in high concentration in specific areas as "stunted abalone," "shorties," or something similar (Shepherd, 1988; Sloan and Breen, 1988; Nash, 1992; Wells and Mulvay, 1995). These are self-recruiting populations completing their life cycles below the regional minimum size of capture. The cause of "stunting" is apparently environmentally, mediated by food abundance and water quality, rather than genetically based. In some cases the density of the abalone population appears to limit growth and the size-at-maturity (Emmett and Jamieson, 1988). While poorly documented in the literature, there are ample anecdotal accounts from the different fisheries of the growth of stunted stocks being improved through culling, and even a few about the reverse, where closure to fishing has led to increased population density and the stunting of individual growth.

Conversely, the original abalone divers in every fishery also talk of "non-recovery bottom," or something similar; areas that only supported a few years of fishing before catches declined to almost nothing. These beds initially supported very high rates of collection because the entire breeding stock was larger than the minimum legal size, but the initial biomass and pre-exploitation recruitment was stripped away in surprisingly few years. The active re-aggregation of abalone around aggregation sites known by divers harvesting makes harvesting so efficient that, when regional size limits permit, it is easy and profitable to drive abalone aggregations into local extinction (Shepherd and Baker, 1998; Shepherd and Rodda, 2001; Shepherd et al., 2001).

The implication of this remarkable plasticity in growth for mariculturists is that hatchery and mariculture conditions tend to reproduce the conditions (relatively low water movement, poor diet, crowded conditions, unstable substrate) likely to produce "stunted" growth patterns, low size-at-maturity, and low average maximum size. Slow growth rates to a low maximum size are compounded by the fact that, as described above, natural growth rates are often over-estimated. Together these factors combine to produce unexpected and unacceptably low production rates of abalone that are too small and too expensive for the international market. This is the primary reason for the continuing lack of mass production of abalone through mariculture.

The plasticity in size-at-maturity, together with the localized scale of larval dispersal, also confounds the management and assessment of abalone fisheries. There was no early appreciation of the extent to which the size-at-maturity varied within the fisheries. Researchers relied on relatively few tagging studies of emergent adult populations to establish single jurisdictional size limits which were then applied over 100s to 1000s km of coastline.

Highly Aggregated Populations

At maturity, cryptic abalone emerge out of the interstitial spaces and move into exposed adult feeding and breeding aggregations on the surface of the reef (Prince, 1989). They do not disperse through their environment, but form dense aggregations at fixed locations. Typically, across all geographic scales 80% of the abalone stock

will be found clumped into 20% of the habitat (Prince et al., 1998). At a scale of 100s to 1000s of meters aggregations are clumped within reef complexes to form self-recruiting populations which are loosely linked within meta-populations (Shepherd and Brown, 1993) that abalone divers call abalone "beds" or "patches."

Divers learn by experience the locations of the abalone beds and their component aggregations (Prince, 1989, 1992). Having learned the location of aggregations, divers need spend little time searching for abalone because they are able to quickly check whether or not abalone have re-aggregated before deciding whether to re-harvest a bed. Consequently, even at the scale of component populations, catch and effort statistics provide a poor index of searching time and catch remains remarkably proportional to effort. Thus catch rates tend to hyperstability and provide poor indices of abundance (Prince, 1989, 1992; Prince and Hilborn, 1998).

Abalone emergence from the interstitial spaces within the reef and movement into aggregation coincides with the onset of maturity, so subject to regional minimum size regulations, the aggregated breeding stock is extremely vulnerable to fishing (Prince et al., 1988b; Prince, 1989). In productive, fast growing areas, local populations of abalone emerge at larger sizes than those in slower growing areas. When uniform legal minimum sizes are applied across an abalone fishery, slower growing breeding stocks with relatively small sizes-at-maturity are given greater protection than more productive stocks with larger sizes-at-maturity (Sluczanowski, 1984, 1986; McShane, 1991).

Unfortunately, fishing pressure concentrates on areas where abalone growth (and hence, recruitment into the fishery) is faster because, by definition, that is where legal sized abalone are most easily collected. Those are also the areas where reproductive potential is least protected. Thus, the least productive "stunted" stocks in "slow-growth" areas will receive great protection from the regional size limit while nearby highly productive reefs, where maturation takes place around or above the minimum size, are depleted. Paradoxically, in this situation a move to protect breeding stock by increasing a regional minimum size limit can result in increasing the concentration of fishing pressure on the most productive, fastest growing beds, thereby accelerating the process of serial depletion (Sluczanowski, 1984; Hilborn and Walters, 1987).

Almost invariably, regional size limits have been set too low; not by mistake, but because of scientific practice. For logistical reasons, researchers with little appreciation of the variability of abalone growth, have generally selected relatively sheltered "stunted" stocks for studies of growth and abundance. The most productive beds are rarely studied because the rough sea conditions that support high growth rates and a large size-at-maturity, make these sites impossible to plan research schedules around. The choice of relatively sheltered research sites, however, has led to legal minimum size limits that only protect the breeding stock in areas with a low size-at-maturity. The main commercial beds of both Australia and New Zealand can be, or have been, fished down to low levels of breeding biomass by regional size limits. The same selection criteria also bias ongoing abundance surveys in Australia and New Zealand because population trends monitored in relatively stunted stocks with low harvest rates and high levels of recruitment are not indicative of the trends observed more generally through the fisheries.

Discussion

The Tragedy of the Commons

In a seminal paper Hardin (1968) described the "tragedy of the commons" by which "each man is locked into a system that compels him to increase his herd without limit in a world that is limited." At that time he was discussing human population control, but noted that it applied generally to the use of most renewable resources including fisheries. Where access is not controlled, competition between users invariably leads to unsustainable pressures on a resource. The long-term communal good is sacrificed to short-term individual benefit. Hardin noted that "freedom in a commons brings ruin to all."

Since the late 1960s, Australia has led the world in promptly limiting access to our most valuable marine resources with the aim of preventing the "tragedy of the commons" diminishing society's marine wealth (Prince and Shepherd, 1992). By the mid-1960s, soon after the commercial abalone fishery commenced, most Australian states had imposed minimum size limits based on the size-at-maturity. Most of the states limited entry during the late 1960s and early 1970s, capping the number of commercial abalone divers in Australia to around 345. When recorded annual catches increased towards a peak of 8200 t in 1985, diver concern prompted the authorities to introduce individually transferable quota systems (ITQs). Total allowable catches (TACs) are nominally reviewed annually and most Australian states administer them within at least 2–3 separate zones, each encompassing 100–1000 km of coastline. Most states are introducing more zonal size limits and sanction the occasional fishing of "stunted stocks." Formal stock assessments are now published in every state.

The prompt application of regional size limits, limited entry, and ITQs in Australia and New Zealand effectively controlled development and stabilized the fishery (Prince and Shepherd, 1992). Despite the superficial appearance of stability, however, the "tragedy of the commons" is still occurring at the scale of microstocks.
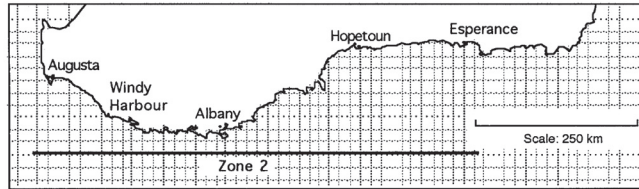
The Tyranny of Scale

In haliotid fisheries, management, monitoring, and assessment occur at spatial scales several orders of magnitude larger than the scale of functional units of stock (Fig. 5). With regional management, fishing pressure focuses on the most favored microstocks: those with a high proportion of legal size abalone, those most accessible to home ports, and those in shallow or relatively sheltered waters. At any point in time, the lower costs associated with fishing favored areas attracts unsustainable fishing pressure while less favored reefs may remain lightly exploited. Over time, as favored microstocks are successively depleted, fishing pressure is reallocated to progressively deeper, remoter, and less heavily exploited areas, or to progressively more "stunted" areas, precisely the areas formerly considered too marginal to attract an unsustainable level of effort. Serial depletion and local extinctions continue below the scale of management, while pressure upon the remaining productive beds steadily escalates, all within the "safe keeping" of a regional quota and minimum size limit. A "tyranny of scale" prevents otherwise effective management strategies addressing the "tragedy of the commons."

The tyranny of scale introduces further complications for stock assessment (Prince, 1989; Prince and Guzmán del Próo, 1993). Catch and effort data are generally aggre-
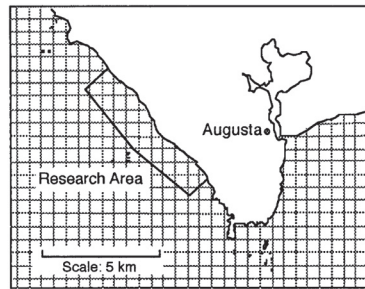
Tyranny of Scale

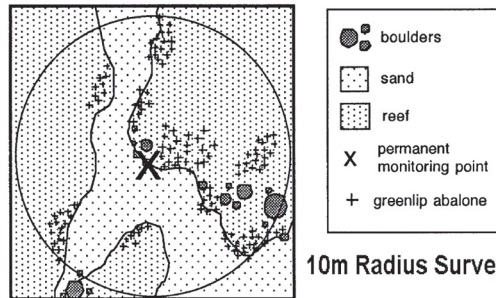**A**

Regional Scale of Management and Enforcement

B

Local Scale of Data Collection and Stock Assessment

C

The Challenge:

Managing at the Scale of Functional Stocks requires Motivated Diver Behaviour

Figure 5. The tyranny of scale whereby the mismatch between the scale of assessment and management, and the scale of highly variable functional units of stock, compromises sustainable management by leaving component units of stock subject to the tragedy of the commons. This figure is reproduced from Prince et al. (1998).

gated over many (tens to hundreds) microstocks which, as described by Prince and Hilborn (1998), form a concentration profile. At any point in time there are reefs with higher and lower catch rates. Favored reefs have lower catch rates while reefs which are visited infrequently for various reasons (i.e., deeper, exposed coast, far from port, too many undersize abalone) offer higher catch rates. By influencing the way divers allocate dive time across the concentration profile of beds, material factors such as beach price and management regimes, rather than stock abundance, drive regional catch per unit effort (CPUE) trends (Prince, 1989; Prince and Hilborn, 1998). Thus CPUE in abalone fisheries tends to be hyperstable at the scale of aggregations and driven by influences other than stock abundance at the regional level. Nevertheless,
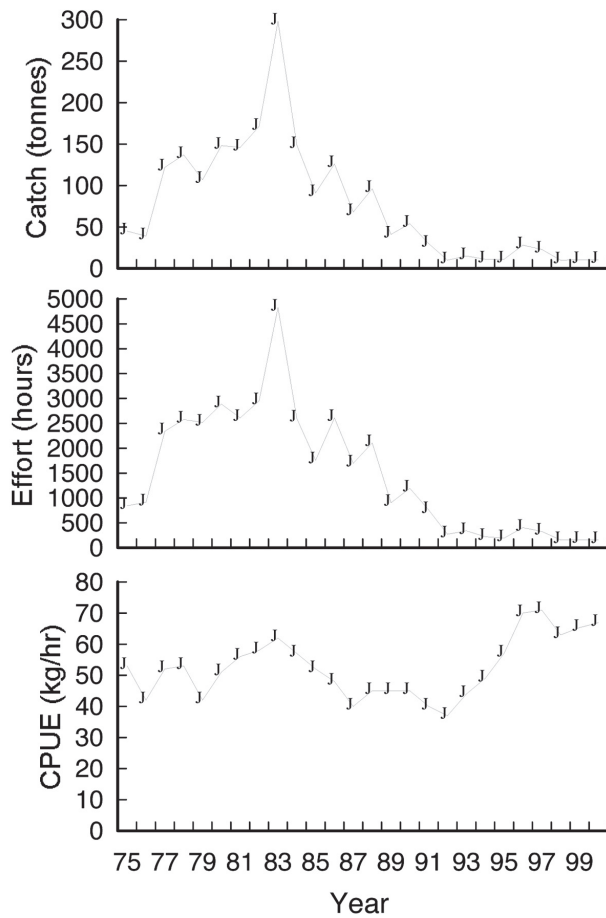
Figure 6. Abalone catch, effort, and catch rates for Tasmanian statistical block 30 for the period 1975–2000. This figure is reproduced from TAFI (2000).

because research surveys are extraordinarily rare, stock assessment processes remain wedded to catch rate data aggregated over tens to hundreds of microstocks.

When surveys of local stocks exist they are normally aggregated over many microstocks, rather than used as indices of trends in abundances of the surveyed microstock. This is because the complementary catch data can only be collected on the larger scale, and there are too few surveys to index a significant proportion of microstocks. Stock assessments typically interpret trends in an abalone fishery as the slow decline of a large and unproductive original biomass (Prince and Guzmán del Próo, 1993). There is never sufficient fine scale data to show the more likely reality, which is the combination of the disparate trends from many smaller but potentially productive populations and serial depletion of the more productive stock units. These biases cause the actual level of depletion to be underestimated along with the aggregate size and productivity of the original resource.

Two Australian Case Studies

The fishery dynamics that result from these facets of abalone biology can be illustrated with two Australian case studies.

St. Helens.—Statistical block 30 of Tasmania was called "The Gardens" by the approximately 15 commercial abalone divers who lived in the adjacent town of St. Helens during the late 1970s and 1980s (Prince, 1989). During that period the divers stably collected 100–150 t yr^{-1} of blacklip abalone (*H. rubra*) in the area from 2000–2500 diving hrs yr^{-1} (Fig. 6; TAFI, 2000). Immediately prior to the introduction of ITQ management, however, effort and catch levels briefly doubled and it can be assumed that this seriously depleted breeding biomass in the area because by 1991 the annual catch had declined to below 25 t and it has never recovered. Effort also declined by >90% so catch rates actually rose by 30%–50%, however, only a couple of divers are now based in St Helens. There have been periodic calls from the Tasmanian abalone industry for government agencies to reseed "The Gardens" with hatchery produced juveniles but to date the depletion has not been reversed.

Cape Leeuwin.—Off Cape Leeuwin, Western Australia there is a smaller but similarly productive area of greenlip abalone [*Haliotis laevigata* (Donovan, 1808)]. In Figure 7 the original size of the abalone is mapped qualitatively and is indicative of the original size-at-maturity through the area. The regional size limit had been set relatively small, preserving 70%–90% of the breeding biomass on the "small" reefs, and moderate levels (< 30%) of biomass on the "small to average" sized areas, but allowing the "average," "average to large" and "large" growing reefs to be legally depleted to near extinction.

With some intuitive understanding of abalone, the local divers at first maintained a voluntary minimum size limit considerably above the legal minimum size limit. Their voluntary size limit preserved 50% of breeding stock on the "average to large" reefs and limited the extent of "non-recovery bottom." This agreement stabilized catches at around 30 t yr^{-1} during the early 1980s, until a diver began using the legal size limit and sparked a short-lived competitive gold rush that substantially reduced breeding stocks on the "average" to "large" reefs. By the early 1990s only "small" and "small to average" size-at-maturity areas were producing reasonable catches, the remainder had become "non-recovery bottom" and production had fallen to 7 t yr^{-1}.

In contrast to St. Helens the decline was reversed at Cape Leeuwin. The divers who triggered the breakdown of voluntary size limits left the fishery and under their own leadership the remaining divers began working collaboratively to rehabilitate the area. Under their "Concept Plan": (1) brood stock translocations were used to rehabilitate some areas; (2) divers were organized to insure that each aggregation was only lightly fished (F ~0.3) once a year; (3) where possible the same diver revisited the same aggregations each year and did not re-harvest if the aggregation had not recovered from the previous years fishing; (4) voluntary flexible size limits were instituted (above the legal minimum size limit) whereby each diver evaluated the size-at-maturity in each aggregation on the basis of shell shape and appearance and only harvested those abalone. Through this plan, production from the Augusta region was rebuilt to > 30 t yr^{-1} by 2001.

Abalone Gardens.—While many localized "one-way" depletions similar to St. Helens could be cited, the example of Cape Leeuwin where a large abalone bed has been rehabilitated is to my knowledge unique. Such rehabilitation does not normally occur because the organizational capacity required to voluntarily implement a complex
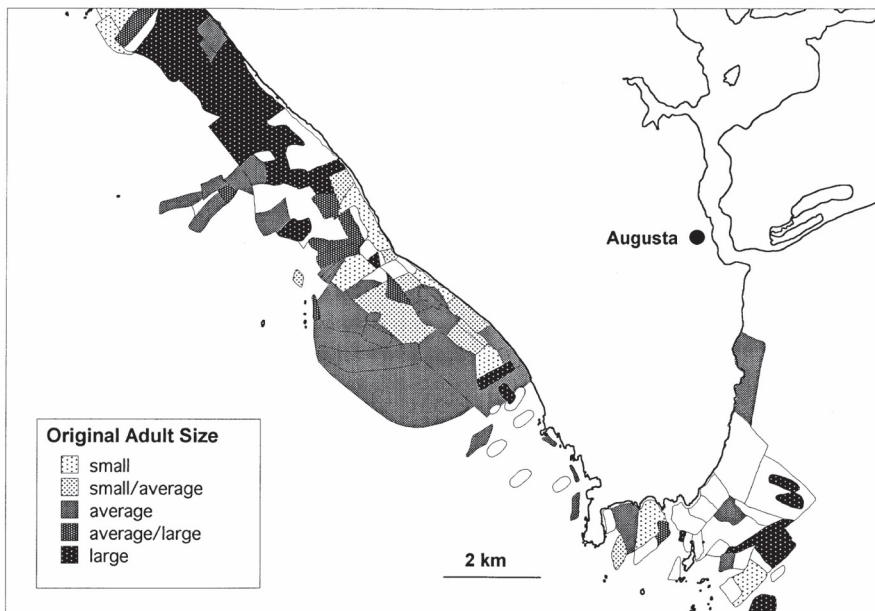
Figure 7. A map of the abalone beds around Cape Leeuwin, Western Australia, prepared in collaboration with the first commercial abalone divers to fish the area. The memory of the divers, together with aerial photography and ground-truthing dives were used to qualitatively map the original "unfished" size distribution of abalone as either small, small to average, average, average to large, or large, which is taken to be indicative of the size-at-maturity. This figure is reproduced from Prince (2003).

of reef-by-reef size limits, quotas, translocations, and closures, is generally beyond competing divers. The "tragedy of the commons" socially constrains people so that they act against the long-term communal good for short-term personal profit. In the abalone fishery this means "If I don't strip the last few mature abalone from that aggregation site the next diver will." Hardin (1968) argued that the "tragedy of the commons" does not have a technical solution, rather it is a social issue requiring society to change and develop new patterns of behavior.

Sustaining and optimizing haliotid production requires maintaining productive breeding stocks in all areas; basically, size and catch limits for each aggregation. Re-introducing and re-building breeding aggregations restores productivity. The technology and knowledge required are simple but the small scale of action required is below the capacity of governments to legislate. The divers themselves are capable of assessing and managing abalone reefs at the small scale required, but currently they have little incentive to sustain and rehabilitate local stocks because there is no secure reward for voluntary long-term good behavior. Their role needs to be developed beyond being marine hunters, competing amongst themselves, and "bringing ruin to all." Through motivation and self-interest divers must be included within the process, and must become marine gardeners, cooperatively tending and harvesting abalone gardens. They are needed as resource surveyors, assessors, managers, and harvesters.

TURF Management

With species subject to the tyranny of scale, some form of territorial user rights fishery (TURF) or customary marine tenure (CMT) can provide the motivation and control needed for local communities and individuals to manage local resources (Orensanz and Jamieson, 1998; Prince et al., 1998). TURFs have considerable precedence. In Europe and North America, many stocks of inter-tidal bivalves are managed as private property and it has been found that this approach maximizes production and minimizes the need for surveillance and enforcement (Beattie et al., 1982; Bourne, 1986).

Japanese Prefectures continue to manage their own fisheries on a basis of local corporate ownership of an area of fishing ground (Mottet, 1980). Despite the ongoing slow decline of Japanese abalone catches in recent times, the relative stability of Japanese commercial catches over 400 yrs suggests that local communities of Japanese fishers have had considerable success in managing their abalone stocks sustainably.

Most marine resources were managed as territorial rights by the traditional societies of Oceania (Ruddle and Johannes, 1983). The displacement of traditional TURF type management and the introduction of a law of the commons framework are encouraging the use of destructive fishing practices (poisons and dynamite). The power of villages, clans, and chiefs to control their own fishing reefs is eroded while the governmental authorities, which nominally take control, lack sufficient resources to monitor, manage, or enforce (Johannes, 1992; De Allessi, 1997). A notable exception to this trend is described by Johannes (1998a) in Vanuatu where a local fisheries biologist began working directly with one community to develop village based management for local trochus snail stocks. The success of this experiment, its rapid and spontaneous adoption by other villages, and application to a range of other species, demonstrate the power for self-organization that can be unleashed if individuals and small local groups are empowered.

Similarly, a form of TURF management was implemented in 1992 for all Chilean diving-based benthic fisheries (Castilla et al., 1998). The most valuable species in the assemblage now being managed by local cooperatives, or *caletas,* is the gastropod *Concholepas concholepas* (Bruguière, 1789), also called loco, the Chilean abalone. The Chilean experience has demonstrated the powerful self-organizing nature of TURF management. Some caletas successfully claimed exclusive access to their own areas and then failed to improve management, but the few that had initial success have proved to be the most powerful influence on the system, providing working examples to which other caletas have aspired, and imitated.

The recent experiences of Chile (Castilla et al., 1998) and Vanuatu (Johannes, 1998a) demonstrate the "learning by doing" approach to management (Walters and Holling, 1990) that local communities and individuals adopt when given local resource ownership.

Needs and Resources

The tyranny of scale is not confined to abalone fisheries but is observed widely across the world's fisheries. Many benthic invertebrate and tropical reef fisheries have the same intricate small-scale stock structure (Orensanz and Jamieson, 1998). At larger scales, teleost and shark fisheries with multiple breeding stocks (Walters

and Cahoon, 1985; Bell et al., 1992; Maurstad and Sundet, 1998; Punt et al., 2000) are all subject to tyrannies of scale effects. I believe that with increasing knowledge, we will find this be the norm rather than the exception.

Dispersal and movement are complex phenomena. Species and populations maintain a range of differing behaviors (e.g., McDowall, 2001). Invariably, a few individuals move long distances in contrast to the majority behavior. Such minority behavior is vital for colonizing new habitat over geological and evolutionary time frames. Without it, natural processes that create and destroy habitat, like sea level changes, would drive many species to extinction. We have tended to link the scale of functional stocks to the maximum distances moved by a species, the longest tagging movements, or the scale of genetic isolation. For management purposes, however, the shorter "normal" distances moved within one or two fishing seasons best indicate the most appropriate scales of functional units for management of a fishery.

The world's fisheries contain a myriad of microstocks, but research and scientific understanding has focused on the conspicuous offshore industrial scale fisheries (Orensanz and Jamieson, 1998). Unfortunately, the technical challenge of managing, monitoring, and assessing the earth's fish stocks is proportional to the number of functional units, not their size or value. Likewise, the cost of the required research, monitoring, and management is not strongly linked to the value of resources, but is more clearly related to the number of units involved. Larkin (1997) had a rule of thumb: that the cost of research and management cannot sustainably exceed 10%–20% of the value of the fishery, but when the cost of a single researcher with government overheads approaches US$100,000 yr^{-1}, what does one do with a fishery that is worth < US$500,000 yr^{-1} but is comprised of a multitude of microstocks?

The role of central government is shrinking, not expanding, as taxpayers demand leaner smaller governments. There are simply too many microstocks scattered across too much area to be surveyed, and too many stock assessments needing development; and not enough taxpayers to pay for it all.

Assuming that the nature of property rights in fisheries can be extended to making more use of territorially based fishing rights: who will service the technical needs of all those local stakeholders wanting to monitor and manage their own microstocks? Not the existing universities and governmental agencies funded by shrinking central governments.

Agents of Change

In the 1950s, China must have faced a similar looking national health problem. Medical skills were required in every village through country but there was a critical shortage of trained doctors. China responded with the barefoot doctor campaign. Not more surgeons and fully trained doctors, but low cost, generalist, medicos trained to go out and deal with all the basic village ailments.

Similarly we can visualize the role of "barefoot ecologists" (Prince, 2003) and can already see the first pioneering practitioners in the field. Barefoot ecologists need to be pragmatic, integrated generalists —ethno-socio-quantitative fisheries ecologists, holistically skilled in the multiple disciplines required to work effectively with microstocks and diverse fishing communities. Over long time frames they will act as agents of change in local communities, catalyzing social development and building social capital within fishing communities. Barefoot ecologists will facilitate the de-

velopment of social structures that foster community-based management, and work to motivate and empower fishers and their communities to research, monitor, and manage their own local resources.

Starting with each local resource and community as an expert in data-less management (Johannes, 1998b), the barefoot ecologist gleans local knowledge and reads the comparative literature to develop recommendations of sensible "rule-of-thumb" management. Their core business in each situation will also involve initiating long-term community-based monitoring systems to start developing time series of basic data, and formalizing simple agreed initial resource assessments. Implementing simple management reforms and monitoring systems will bond a barefoot ecologist with a community of fishers and establish the long-term context for providing the expertise needed to update assessments, and facilitate community dialogue about alternative management strategies. Working organically with local resource users, a growing army of barefoot ecologists, each with a portfolio of clients, could hope to extend sustainable practices across the world's oceans and seas.

None of this is meant to suggest a reduced role for government agencies or academic institutions in the field of fisheries science and management. It is a call for clearer thinking about differing but complementary roles. Government agencies need to develop legislation that supports the evolution of social systems, like TURF and CMT, which encourage sustainable small-scale behavior. Government also needs to legislate to protect broader "non-fishing" community approved standards, providing for checks and balances, and establishing auditing procedures. Specialized expertise will always be needed to train and equip barefoot ecologists and research agencies and universities will still need to discover and publish novel scientific knowledge, and develop innovative techniques and tools for practitioners to use (Prince, 2003).

Conclusions

The inability to adequately sample juvenile abalone populations has seriously compromised much of the published research, confusing studies of growth, ageing, mortality, and recruitment. Where this weakness has been overcome, abalone resources have been revealed as spatially complex patterns of relatively self-recruiting microstocks with highly variable growth rates and sizes-at-maturity. The small scale of these microstocks and sheer number of management units present specific problems to centralized fisheries research and management agencies.

While I have illustrated these ideas by reference to abalone it is my belief that over a range of scales they are generally applicable to most sedentary invertebrates, and for many teleosts and chondrichthyans. I expect that as our knowledge of stock structure matures, small-scale population structure and self-recruiting microstocks will prove to be surprisingly common through the world's fisheries resources. My belief is that most, if not all, species exist in complexes of microstocks or meta-populations, although the scale of the microstocks meta-population varies enormously among species. Haliotids clearly operate at some of the smallest scales, but I believe as a general rule, population dynamics operate over smaller scales, while species maintain a long-term dispersal capacity needed for gene flows and colonization.

It is also my belief that the variability in growth and size-at-maturity documented for abalone will also prove to be common among component microstocks of many species, rendering them vulnerable to tyranny of scale effects. Moreover, it is also

likely that natural mortality regimes and stock-recruitment relationships commonly vary among microstocks of many species. It is probably a reflection on the quality of our research (relatively few studies of basic population parameters for each species, inadequate sampling of cryptic life stages, and insufficient ageing studies, etc.) that obscures this natural variability in most species.

The challenge with these spatially structured resources is firstly, to adapt techniques for data collection, stock assessment, and management, from scales of hundreds to thousands of kilometers down to scales of tens to hundreds of meters for abalone, and secondly, to find the resources needed to apply these techniques across a multitude of microstocks. I argue that harnessing the motivated behavior of fishers by making greater use of territorially based fishing rights will be essential to addressing this challenge. I also believe a new class of practitioners in the field of fisheries science will be essential to answer the many technical needs of local fishers, their communities, and their TURF.

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